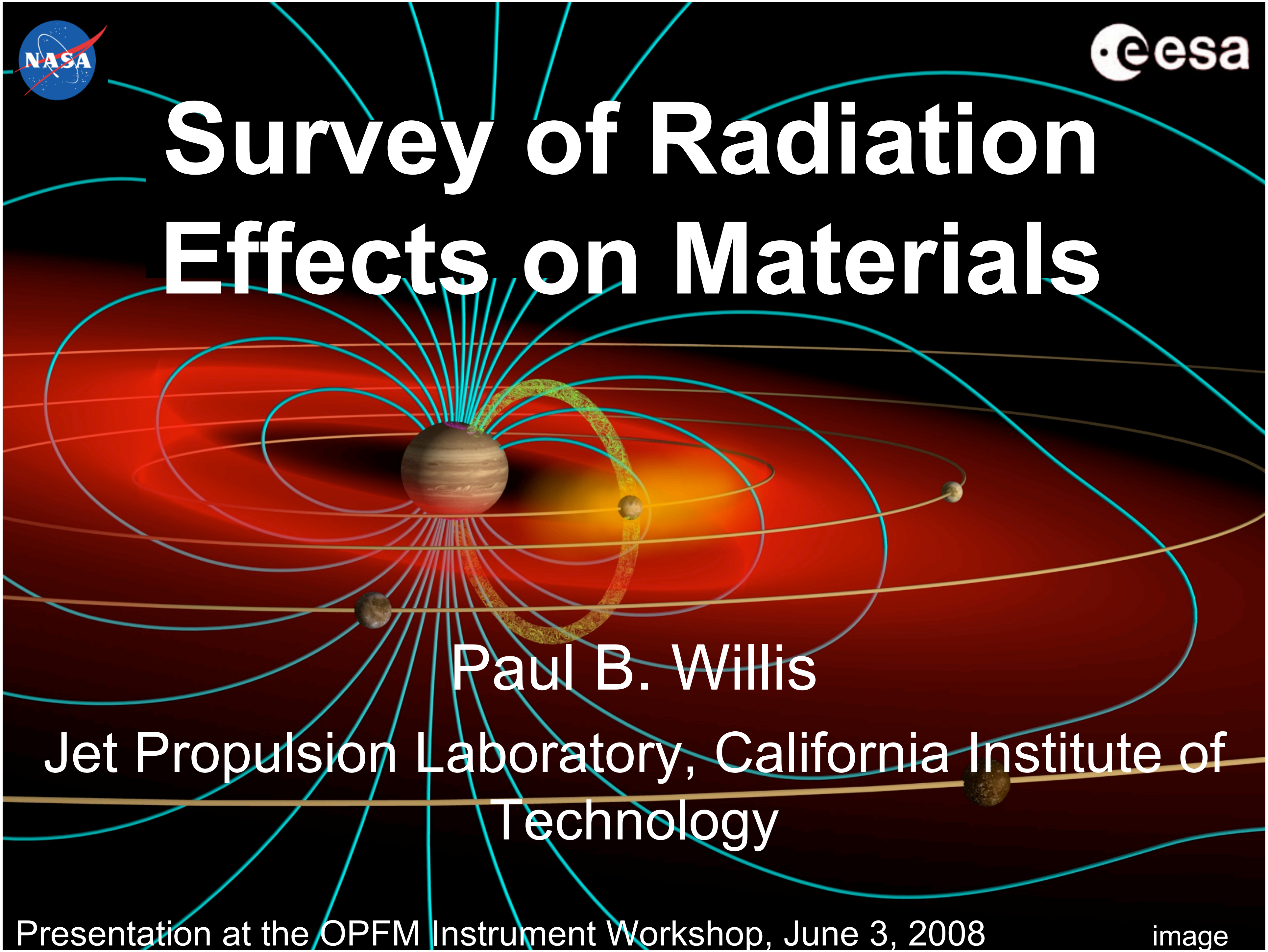

Survey of Radiation Effects on Materials

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Current Literature Data

BULK	LIMITING	
MATERIAL	**DOSE (Rads)**	**NOTES**
Multi-Layer Insulation	> 1 E +8	Verified data
Polymers	1 E+7 to 1 E+9	Typical range
Adhesives	1 E+8	Typical, always shielded
Composites, epoxy	1 E+8	Onset of change dose
Composites, cyanate	1 E+9	Onset of change dose
Cabling (SPEC 44/55)	5 E+8	Verified data
Lubricants	1 E+6 to 1 E+9	Used in shielded environment
Seals/elastomers	5 E+7	Used in shielded environment
Glasses	1 E+5 to 1 E+10	Depends on composition
Ceramics	1 E+12	Typical value
Metals	1 E+18	Typical value
Fuel (hydrazine)	1 E+6	1% decomposition noted
Note: "Bulk" does not include surface damage		

(Note: All doses are Co ^{60} gamma exposure in air)

Metals

- Charged particle ionization no problem as the valence electrons in metals are all “ionized” anyway, and occupy the conduction band
- Metals are prone to displacement damage (DDD) from energetic neutrons, and essentially inert to the space radiation – however - DDD contribution may be caused by electrons and protons
- Non-Ionizing Energy Loss (NIEL) may result in heating
- The resistance to charged particle damage is clearly shown by metal targets used in linear accelerators and other machines producing very high energy charged particles
- “Equal dose = equal damage” concept does not apply to metals

Permanent Magnets

- Most magnetic metals acceptable for use
- Permanent magnets are an exception
- (Nd-Fe-B magnets lose 10% magnetic remanence after exposure to fluence of 10 E+15 n/cm2 due to reversion of domains by collision damage. Protons more damaging at 500 MeV resulting in 55% loss at fluence of 10 E+14 p/cm^2
- Sm-Co magnets better; 2% remanence loss after 1.1 E+18 n/cm^2 fluence)

Ceramics

- Principal damage in ceramics is due to atomic displacement and disruption of the crystal lattice.
- Increase fragility of *some* ceramics noticed at doses as low as 10^6 rads of charged particle radiation
- Generally, damage does not usually occur until very high doses are reached (ie. 10^{12} rads)
- The resistance to charged particle damage is clearly shown by ceramic components used in linear accelerators and other machines producing very high energy charged particles.

Carbon / Carbon Composites

- Ceramic composites generally of little concern.
- Carbon/Carbon composites and graphites are virtually immune to ionizing radiation (but known to change density at high neutron fluxes 1 E+20 n/cm^2)
- Carbon/carbon a possible concern with ion thrusters (NASA Glenn)

Optical Glasses

- Optical glass may be shielded, but outer surfaces may receive very high surface doses, and dominated by protons
- Radiation effects may include: f-centers, G-centers, displacement damage, internal space charging. Damage effects may include: darkening, internal arcing, density change, fracture
- Radiation resistant glasses formulated with cerium oxide for stability; include Schott BK7G18, K5G20, LF5G15, SK4G13, SF6G05, others. Test data (electron, proton gamma) show 20% loss in transmission at 1E+5 to 1E+6 rads
- Voyager narrow angle camera used Suprasil III pure silica
  - No %Transmission change at 1E+16 rads 0.8 MeV electrons, 1E+8 rads protons at 2 MeV (no fluorescence)
- Corning 7940 has excellent radiation resistance.
  - Minor changes at: 6.3 E+14 rads electrons (800 keV), >10 E+4 rads 2 MeV protons, and 10 E+20 n/cm^2
  - Fluorescence may occur from Cherenkov radiation (charged particles only)
- Acceptable glasses commercially available; may require testing.

Optical Coatings

- Coatings are used for anti-reflection, or refractive index matching purposes. Typical materials are silicon dioxide, tantalum pentoxide, magnesium fluoride, zinc sulfide and thorium fluoride
- Optical coatings may be partially shielded from full radiation environment. Likely to take very high surface doses and suffer from proton damage
- Very short optical path length (microns) usually prevents serious radiation induced losses in the visible region
- Development of surface potential and dielectric breakdown is a more serious threat to survival
- Tantalum oxide and silicon oxide coatings proven in multi-gigarad service on solar cell cover glasses. (Threshold damage values of 1E+12 rads)
- More literature research required; possible testing
- Concern: protons at very fluences may erode surfaces by sputtering

Polymer Radiation Chemistry

- Generally accepted: “equal dose gives equal damage”, regardless of radiation type. (Note that dose-depth profiles may be different!)
- Charged particles above the electron binding energy eject an electron from the atom, resulting in ionization. Particles below the binding energy may form excited states that generate free radicals (unpaired electrons), and/or a number of other chemical species
- Gamma rays produce electrons by Compton scattering
- Neutrons may contribute to ionization from recoil electrons
- Combined pathways may be complex, but usually lead to either:
  - (a) crosslinking
  - (b) chain scission
- <u>Crosslinking</u> results in: decreased elongation, increased tensile strength, increased modulus
- Chain <u>scission</u> results in: brittleness, fracturing, gas generation, and sometimes depolymerization back to a liquid state
- In general, hard glassy polymers that crosslink are more resistant to radiation damage than soft or flexible polymers
- Note: in the presence of air, oxygen reacts strongly to generate oxygenated species, discoloration, molecular weight degradation, and much lower limiting doses. The <u>absence</u> of air during radiation exposures is essential!

Polymer Radiation Chemistry

- Gas evolution happens in almost all polymers under irradiation (mainly hydrogen, but also methane, CO_2 and others). Gas evolution is approximately 0.1 ml (STP) / gram per Mrad absorbed energy. Pressure in sealed systems is a potential problem
- Radiation induced electrical conductivity is found in most plastics (due to ions), and induced current is a function of dose rate
- Conductivity usually decays exponentially over periods of days or months
- Aromatic (benzene) rings impart the highest radiation stability to polymers due to resonant energy dissipation mechanisms
- The addition of mineral fillers may add another order of magnitude stability
- Phenolics (phenol-formaldeheyde resins) and polystyrene can withstand doses up to 8 E+9 rads TID with minor loss of mechanical strength
- All polymers are at risk; dose and damage assessment required
- Dose usually expressed as “TID” (Total Ionizing Dose)

Elastomers

- Gaskets, seals and O rings are used in highly shielded environments. Should be tested to an estimated actual dose.
- Fluorinated elastomers have excellent corrosion resistance, but are not as good under radiation. (Viton, Kalrez, Aflas and Fluorel rubbers show changes at 1E+6 rads, moderate damage (50% tensile) at 2E+7 rads).
- Phenyl silicone rubbers tensile strength good to 1E+7 to 1E+8 rads TID.
- EPR (ethylene-propylene rubber) (Eg. AFE-411 and AFE-322) have threshold values of 5E+7 rads. Unusable at 5E+8 rads TID.
- Elongation and compression set sensitive to much lower levels (valves?)
- Current gaskets and elastomers may be usable in Europa mission providing that shielding calculations verify acceptable dose levels.
- General rule: avoid “soft goods” if possible and go to metallic seals or flexible components.

Cables and Wiring

- Cable and wiring insulations are a concern; most wiring is internal to spacecraft and shielded, but cables may be exposed in bus, thruster and antenna deployment areas
- Kynar insulation retains 60% tensile strength at 1E+9 rads TID. Often used in a pre-irradiated form to impart stability
- Raychem Spec-44 and Spec-55 cables tested to 5E+8 rads TID, no effect on performance. May need to be metal foil wrapped for additional protection. (Used successfully around RTGs)
- Internal charge build-up is a potential problem. Polymer conductivity goes up in high radiation fields, but charge accumulation may result in internal arcing
- Rad-hard cables with <u>ceramic</u> insulation are available; should work fine
- Cable testing and connectors; validation required
- What does nuclear industry use?

Adhesives

- All adhesives are used in highly shielded environments. Should be tested to estimated actual dose - not external environment levels
- Typical hard adhesives maintain properties to about 1E+8 rads
  (Eg. 3M EC2216, Hysol EA9394, Hysol EA-9309, Stycast 2850)
- Low modulus silicone adhesives also have threshold doses1E+8 rads TID.
  (RTV 566, Dow Corning DC 93-500 (solar cells) and CV-2510)
- Current adhesives may be usable in Europa mission providing that shielding calculations verify acceptable dose levels
- Testing of adhesives in critical areas required

Carbon Fiber & Glass Composites

- Composites derive their high strength, high modulus and low CTE properties from shear coupling carbon fibers in an organic matrix
- Carbon fibers have high radiation resistance and protect the organic phase from damage
- Conventional composites use epoxy matrix materials with generally high radiation resistance (1 E+8 rads)
- Newer “cyanate” matrix composites have better radiation resistance. These compounds (175°C cure) have highly aromatic chemistry

  (Exposure to 1 MeV electrons show no change at 1 E+9 rads)
- The 120°C cure cyanates (“antirad” chemical structure) are better yet

  (Estimated limiting dose > 1 E+10 rads)
- Carbon-Carbon Composites: completely pyrolyzed, no organics remain. Resistant to charged particle radiations at high levels
- Testing of organic composites in critical areas required

Multi-Layer Insulation
(Thermal Control Blankets)

- Unshielded surface exposure; the worst mission condition. Surface doses in the tens of gigarads range expected due to proton fluence
- Most thermal blankets are Kapton polyimide, and contain carbon black for additional stability. (Avoid Teflon films!)
- At 1E+9 rads (^{60}Co gamma) Kapton retains 73% strength, 50% elongation and 90% modulus. Other sources report mechanical stability to 5E+10 rads
- LaRC polyimides, CP-1 and CP-2, tested to 5E+9 rads with no property change. Possible alternative to Kapton if necessary
- Electrostatic dissipation (ESD) coatings available (Shedahl). Transparent coatings appx. 100 Angstoms thickness with conductivity of 10K ohms per square are effective
- ESD coatings based on sputtered indium-tin oxide (ITO) should have radiation resistance of typical metal oxides, 1E+12 rads. (No data)
- Testing absolutely required due to very high electron and proton fluences
- Concern: proton fluences are so high that surfaces may erode from sputtering

Teflons

- Teflon is produced in four main grades: PTFE (poly-tetrafluorethylene), FEP (fluorinated ethylene propylene), and PFA (perfluoroalkoxy) and MFA (perfluortetrafluoroethylene-perfluorovinyl methy ether)
- Teflons degrade by chain scission, with reductions in elongation, tensile strength and volume resistivity
- Most of the published Teflon data is fifty years old, and is for gamma ray exposure of PTFE in air. Limiting dose is stated as 1.5 E+4 rads (25% decrease in ultimate strain)
- PTFE: Oxidation effects are large. Limiting dose goes to 1 E+5 rads in vacuum or under inert fluid, and 1 E+6 rads under 1200 psi static pressure
- FEP: Limiting doses appx. 2.4 E+5 rads in air, and 1 E+6 rads in vacuum
- PFA: Limiting dose (2 MeV electrons in air) about 5 E+6 rads TID
- All “Teflons” are not equal, in chemistry or radiation resistance
- Teflons have widespread and successful use in spacecraft wire insulation
- Need a complete, and documented, re-evaluation

Lubricants

- All lubricants used in highly shielded applications.
- Chemical ranking of stability: polyphenyls > phenyl ethers > alkyl aromatics > fluorinated ethers > aliphatic ethers > aromatic esters > silicones
- Current space qualified lubricants include Bray and Krytox oils (PFPE)
 (Tested to 1 E+8 rads (^{60}Co) and 1 E+8 rads 1 MeV electrons)
- Pennzane 2000 (MAC) oil tested to 1 E+6 (^{60}Co)
- Nye 8XX oils (polyphenyl ethers): tested to 1 E+9 rads, no change
- Dry lubes such as Dichronite (tungsten disulfide) and Lub-Lok 4306 (graphite in polymer binder) tested to 1 E+9 rads; wear life actually improves!
- Current lubricants may be usable in Europa mission providing that shielding calculations or testing verifies performance
- Dry lubrication systems preferred due to the much higher radiation resistance

Thermal Control Paints

- Direct surface exposure; the worst mission condition. Surface doses in the tens of gigarads range expected due to proton fluence
- Typical white paints include Z-93, NS43G, Hincom. Consist of inorganic pigments in a potassium silicate (Kasil) binder
- Binders: potassium silicate (Kasil) essentially radiation resistant. (Avoid white paints with silicone binders - eg. S13 GP/LO)
- Current best choice is Hughes M-1 paint; radiation stable to 14 years in GEO and resistant to proton damage
- Black paints: typical products include Z-306, MH-2200, Z-004/SC, and all have organic urethane binders. Not likely to survive the Europa surface dose
- New metal oxide black paints exist (eg. QS-1), with claims of high radiation resistance. No further data at this time
- Thermal control paints will have to be qualified to full mission fluence of protons
- Concern: proton fluences are so high that surfaces may erode from sputtering
- High energy particle effects currently unknown

Propellants

- Propellants contained in shielded environments. Should be tested to estimated actual dose - not external environment levels
- Radiation data scarce!
- Electric propulsion: Xenon completely resistant to ionizing radiation
- Chemical propulsion: hydrazine tested to 1E+8 rads with stated decomposition of <2%
- Xenon of no concern. Chemical propellants (and pyros) may require exposure testing

Preliminary Test Findings (JIMO Studies)

- A number of “representative” materials were exposed to 4.5 MeV electrons under inert gas
- Teflon® PTFE and FEP maintained usable properties to 2 x 10^{7} rads; three orders of magnitude better than literature values for ^{60}Co gammas in air
- EPDM and silicone rubbers maintained usable properties to 2 x 10^{8} rads; two orders of magnitude better than literature values for ^{60}Co gammas in air
- Kynar® and Tefzel® cable insulations began degrading at 2 Megarads; wire and cable insulations may be at high risk
- Kapton® Torlon®, PEEK®, Vespel®, IR grade quartz, sapphire and epoxy-graphite composites all showed no degradation at 1000 Megarad equivalent doses. Highly stable to electron ionizing environments
- Current electron testing does not correlate well with gamma results, but…
- Results are encouraging

Gamma Radiation Data

(Literature Data)

- Most radiation data is for gamma exposure in air (not electrons/protons in vacuum)
- Damage dose increases by one order of magnitude in vacuum
- Much data is sixty years old and dosimetry is rarely, if ever, reported (actual dose unknown)
- Many modern materials are not included (eg. PEEK, Kalrez, fluorinated oils, thermal control paints, etc.
- Dose-depth profiles for gammas do not match electron/proton spectrum – so surface doses may be higher for charged particles, and internal doses lower
- Gammas have three modes of physical interaction: (a) photoelectric effect – 0.01 to about 0.5 MeV, (b) Compton scattering – about 0.3 MeV to 8 MeV, and (c) pair formation (electron/positron), 5 MeV to 100 MeV. Ionization is a secondary effect
- Electrons effects are dominated by a single interaction: ionization Dose-depth note: At 1 MeV *protons* penetrate approximately 1/100 the distance of the *electron*, and gammas penetrate appx. 50 times the depth of the electrons
- Critical properties of interest (like dielectric constant, or dielectric breakdown voltage) are not usually measured
- Gamma data has little relevance to space environment conditions (except w/ RTGs)
- Preliminary data from electron exposure shows discrepancies

Conclusions

- Much of the published materials data is ^{60}Co gamma ray exposure in air environment, and is 50 years old. Questionable applicability to Europa conditions
- Although gamma rays are ionizing, damage cannot be realistically simulated due to different dose-depth curves and different physics of interaction; probably useful for rough screening
- Metals, ceramics and carbon composites generally exempt from concern
- Optics and optical coatings require careful selection for survivability
- Polymers, elastomers and adhesives require evaluation
- Thermal control paints, blankets and cabling may be at the highest risk
- Insulators may be at high risk due to charge accumulation and arcing
- Materials stopping powers, and differing penetration depths should be tested with a closer match to the Europa mission dose-depth curves
- ***Conclusion: Electrons and protons should be used to determine both ionization and displacement effects as a closer simulation to the Europa radiation environment***

Questions & Answers